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Texas A&M University

Mechanical Engineering Department

College Station, Texas 77843

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Gerald L. Morrison

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Hampton, Virginia 23665

TEXAS A&M UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
COLLEGE STATION, TEXAS 77843-3123

April 21, 1982

Dr. Jim Yu
NASA Langley Research Center
Mail Stop 460
Hampton, Virginia 23665

Dear Jim,

Enclosed is a copy of a paper we have submitted to ASME for presentation at the ASME Winter Annual Meeting. The paper includes the acoustic phase fronts that we were able to measrue using a Nicolet 660A dual channel spectrum analyzer. The technique worked only marginally well since results were obtained only over a very small region of the jet. Therefore, we are setting up a microprocessor based data acquisition system which will enable us to use various methods for extracting the phase information. The same data acquisition system will be used for the crossed hot-wire measurements.

Yours truly,

G L Morrison

G. L. Morrison
Associate Professor

TELEPHONE 713-845-1251

NEAR FIELD ACOUSTIC MEASUREMENTS IN NATURAL AND ARTIFICIALLY EXCITED HIGH SPEED SUBSONIC JETS

by
K.W. Whitaker*
and
G.L. Morrison*
Texas A&M University
Mechanical Engineering Department
College Station, Texas 77843

ABSTRACT

Acoustic measurements have been made in the "near" ($r/D < 60$, $x/D < 60$) field for high Reynolds number (184,000 to 262,000) axisymmetric cold air jets exhausting at atmospheric pressure. These measurements were in conjunction with an investigation which characterized the large scale coherent structure in the flow field of Mach number 0.6 to 0.8 jets. Natural jets as well as artificially excited jets were studied. Directivity plots were made for both natural jets and jets excited at various frequencies. Overall noise radiated by the jets was found to reach a maximum value around 30° from the jet axis. However, individual frequencies emitted maximum SPL at different angles from the jet axis. As the angle from the jet axis increased, the spectra of the noise shifted to higher frequencies. Axial wave number-frequency measurements were utilized to produce a relationship

*member ASME

between phase velocity and frequency. It was found that the coherent structure's axial wave speed decreased with decreasing frequency much in the same way the angle of peak noise emission decreased with decreasing frequency. We propose that it was this slowing down of the wave speed that caused the decrease in the peak noise emission angle. The noise production mechanism in the jet was found to be more responsive to mid-band excitation frequencies. Excitation at these frequencies caused a small increase in SPL at the frequency of excitation, but a much larger increase in full spectrum noise. Segments of acoustic phase fronts were measured indicating that some of the noise produced by the jet could be directly attributed to the large scale coherent structure. The origin of the phase fronts was found to be located in the potential core region of the jet.

NOMENCLATURE

Symbol	Description
C_{ph}	phase velocity of disturbance
D	diameter of the jet
f	frequency (Hz)
k	complex wave number
k_i	imaginary portion of k
k_r	real portion of k
M	Mach number
n	azimuthal mode number
Re	Reynolds number ($\rho U_o D/\mu$)
r	radial distance from the jet centerline
St	Strouhal number (fD/U_o)
U_o	centerline velocity at the exit of the jet
x	downstream distance from the nozzle exit
λ	axial wavelength
θ	azimuthal angle
ϕ	relative phase
Φ	angle from jet axis
ρ	density
μ	viscosity

I. INTRODUCTION

The existance of orderly structures in axisymmetric jets of air has been well established since the first observations by Mollo-Christensen[1-2]. Since that time, the role of large scale coherent structures in the noise generation process of jets has been analytically and experimentally investigated by many investigators[3-32]. Some of the theories developed predict that organized structures in the jet are of prime importance in the noise production mechanism.

For low Reynolds number, transonic and supersonic jets[14,15,20-22,26], large scale organized structures which cause a major portion of the radiated noise have been experimentally confirmed. In subsonic jets, many experiments have been performed in order to determine the noise production mechanism. Mollo-Christensen[1-2] first observed the coherent structure in subsonic jets ($0.15 < M < 0.9$) by using space-time correlations in the near pressure field. He also measured far field noise spectra and directivity patterns. It was believed that the organized structure radiated acoustic energy more effectively than a random structure.

Crow and Champangne[7] examined the organized structure in very low speed jets of air ($M < 0.1$) by using a speaker to artificially excite the jets in the

axisymmetric mode ($n=0$). They used both hot-wire anemometry and flow visualization to identify the flow field. It was concluded that there was an orderly structure in the jets and this structure could be approximately characterized by a linear stability theory.

Maestrello and Fung[13] used microphones in the near acoustic field of a turbulent Mach number 0.669 jet in order to study the large scale structure. They found that the large scale structure originated near the jet exit which appeared first as a roll up on the mixing layer of the flow within one diameter from the jet exit, became fully developed at approximately three diameters and disappeared beyond the end of the potential core. The Strouhal number based on the most probable frequency for the fully developed structure was in the range of 0.3 to 0.4. The convection velocity was relatively low at the exit of the nozzle, reached a maximum at the end of the potential core, and decreased as the flow progressed further downstream.

The present research was conducted to determine the Mach number dependence of these coherent structures (see [24,32]). Acoustic measurements were made in conjunction with the flow field measurements. This paper will present the results of these acoustic measurements and investigate relationships between the coherent structure and the noise emitted.

II. EXPERMENTAL APPARATUS

Facility

In this present study, three Mach numbers (0.6, 0.7, 0.8) were considered. The experiments were performed in the free jet test facility shown schematically in Figure 1. Round axisymmetric air jets 1.25 cm in diameter were exhausted at atmospheric pressure into an anechoic chamber. Compressed air was supplied by a reciprocating compressor to a 30 cm diameter stilling chamber by way of a storage tank, water aftercooler, water separator/filters, an electronic pressure regulator, and a muffler. The stilling chamber consisted of sections of foam rubber, perforated plates, honeycomb, and several fine screens. The nozzle used had a contour described by a third order polynomial and the contraction ratio from the stilling chamber to the nozzle exit was over 200:1. The jets had a stagnation temperature of 293°K. This flow system resulted in a jet with uniform parallel flow at the exit and a low level of turbulence.

Instrumentation

Acoustic measurements were made using Bruel and Kjaer condenser microphones. Depending on the frequency being studied, either a 1/4 or 1/8 inch microphone was used. All microphones were calibrated with a Bruel and Kjaer model

4220 piston phone. Signal conditioning (band pass filtering and amplification) was performed by TSI 1057 signal conditioners. Two General Radio 1564A Sound and Vibration Analyzers were used to bandpass filter at either 1/3 or 1/10 octave. Acoustic spectra and cross correlations were performed using either a Nicolet 660A Dual Channel Spectrum Analyzer or a Saicor SAI 42 Correlation and Probability Analyzer.

For some measurements, an artificial excitation device was used to stabilize the jet modes into one plane of oscillation or to provide a phase reference for measuring acoustic phase fronts. The device operated by generating a sufficiently large voltage to create a spark across a 1.5 mm gap between two electrodes. The electrodes were 1/16 inch diameter thoriated tungsten rods which had been ground to fine points. This spark effectively put a small controlled disturbance in the jet. These electrodes were mounted on the bottom of the jet nozzle ($\theta = 180^{\circ}$) and at the exit plane of the jet (x/D=0). The electrode points were put into the shear layer with one electrode further into the jet than the other so that the spark would jump across the shear layer.

III. EXPERIMENTAL RESULTS

Jet Operating Conditions

The present research was undertaken to investigate and experimentally identify the large scale coherent structure in the flow field of Mach number 0.6 to 0.8 jets along with the associated noise production. Table I shows the Mach numbers investigated along with their corresponding Reynolds number and value of D/U_o, which was used to nondimensionalize frequency. (In this study all frequencies are presented in terms of the nondimensional Strouhal number, St).

Table I

Jet Operating Conditions

M	Re	D/U_o(sec)
0.6	184,000	.0000632
0.7	221,000	.0000548
0.8	262,000	.0000486

SPL Contours

Sound pressure level (SPL) contours were measured in the "near" ($r/d < 60$, $x/D < 60$) field of the natural M=0.6 jet and can be seen in Figure 2. These contours seem to indicate that for this jet, the noise was generated from a

location near the end of the potential core ($x/D=5$). This axial location also corresponds to where the mass velocity fluctuations reached a maximum level[24,32]. The contours obtained for this jet compare favorably with the measurements made by Stromberg[25] with a low Reynolds number $M=0.9$ jet, and also with the measurements of Mollo-Christensen[2] for high Reynolds number, $M=0.8$ and $M=0.9$ jets. The maximum sound pressure level measured in the acoustic field was 122 db.

SPL Directivity

The sound pressure level as a function of the angle from the jet axis (Φ) was measured for all three of the jets studied. These measurements were made at a constant radius of 36 diameters from the nozzle exit. This data is presented in Figure 3. The overall SPL increased with increasing Mach number and, in all three cases, reached a maximum at 30° from the jet axis. This is consistent with the findings of Mollo-Christensen et.al.[1] who also found that the noise reached a maximum at 30° for a high Reynolds number $M=0.9$ jet.

Artificial excitation was used to stabilize the jet and to provide a phase reference for the characterization of the coherent structure in the flow field and the measurement of acoustic phase fronts. To determine the effect artificial excitation had on the acoustic field, the

SPL as a function of the angle from the jet axis (Φ) measurements were repeated for the excited M=0.6 jet. The microphone signal was bandpass filtered from St=0.063 to 1.264 while the jet was excited at each of six arbitrarily selected frequencies. The results of these measurements can be seen in Figure 4. As the frequency of excitation was increased from St=0.158 to 0.474, the peak SPL increased from 98 db to 102 db. In addition, at St=0.316, the noise became less directional and hence the overall SPL increased substantially. Increasing the Strouhal number from 0.474 to 1.264 resulted in the peak SPL decreasing with increasing frequency. This illustrates that the noise production mechanism in the jet is a more effecient noise producer when excited at the mid-band frequencies. This also happens to be the frequency range where the majority of noise is radiated as observed by other investigators. It should be pointed out that the noise generated by the artificial excitation device was measured with the flow off. When corrections were made to the SPL measurements in Figure 4, the SPL amplitude changed less than 0.2 db. Therefore any noise produced by the excitation device directly was deemed negligible.

Individual frequencies were studied by 1/10 octave bandpass filtering the microphone signal about the excitation frequency. These individual frequency measurements are shown in Figure 5. Shown in this Figure

are the natural jet sound pressure levels along with the excited jet sound pressure levels. In all cases, the excited jet levels are slightly higher than the natural jet levels. The largest differences occurred when the jet was excited at St=0.948 and St=1.264. The slight increase in SPL was probably due to the exciter slightly enhancing the coherent structure fluctuation amplitude at the frequency of excitation and hence increased the noise at that frequency. In Figure 4, it was shown that considerably more noise was produced when the jet was excited by mid-band frequencies. However,this magnitude of increased SPL was not evident in the individual frequency measurements. This indicates that excitation at the mid-band frequencies increased the broad band noise in addition to the noise at that individual frequency.

Spectra were also recorded at various angular locations from the jet centerline for each of the jets and can be seen in Figures 6, 7, and 8. An obvious trend observed in these spectra is that the frequencies in the jet shift towards higher values as the angle from the jet centerline (Φ) increases. This phenomenom is also observable in the individual frequency directivity plots (Figure 5). An explanation for this angular dependence of the frequencies in the jet was given by Mollo-Christensen and Narasimha[33]. They postulated that a sound wave traveling in the downstream direction will be moving at the

speed of sound with respect to the air in the jet and with a Mach number of M+1 with respect to the outside air. The noise transmission will therefore be at an angle given by:

$$\Phi = \cos^{-1}(1/1+M)$$

Sound waves moving obliquely to the jet axis will be transmitted and reflected by the shear layer. This will cause certain long wavelengths to resonate back and forth across the jet. All waves will be radiated according to the equation stated, but by the time the waves which have been bounced back and forth many times are radiated they have been carried downstream into a region where the Mach number has decreased. Thus if M has decreased the value of Φ will be smaller. This would account for the low frequency maxima near the jet axis and the the high frequency maxima further away from the jet axis.

The above explanation was proposed without detailed information about the characteristics of the coherent structures in the jet which produce the noise. We have measured the axial wave number-frequency relationship for the jets currently being studied and have compared them to results obtained by other investigators[3,21,26,30]. Detailed results of these measurements have been presented in reference [24]. A synopsis of the results are shown in Figures 9 and 10.

Figure 9 shows the axial wave number-frequency relationship for both natural and artificially excited jets

with Mach numbers greater than 0.3. The same relationship between the axial wave number and frequency was found for all of these jets. For these jets, the Reynolds numbers ranged from 3,700 to over 500,000, the Mach numbers ranged from 0.3 to 2.5, and some of the shear layers were laminar and others were turbulent with various thicknesses. A linear curve fit of all the data using a least squares method shows that wave number-frequency relationship can be expressed by:

$$k_rD = 0.7735 + 7.226*St$$

This expression can be rearranged further to produce an equation relating the axial wave speed of the disturbance (phase velocity, C_{ph}) and frequency. Realizing that $C_{ph}=\lambda f$, $St=fD/U_o$, and $\lambda=2\pi/k_r$, the following expression can be obtained:

$$C_{ph}/U_o = (2*\pi*St)/(0.7735+7.226*St)$$

A plot of this relationship can be seen in Figure 10. This figure reveals that above a Strouhal number of about 0.4, the phase velocity (C_{ph}) remains fairly constant at 75% of the jet exit velocity. Below St=0.4, the phase velocity decreases with decreasing frequency. This phase velocity variation at low frequencies was also noted by Troutt and McLaughlin[30].

In light of the above sound emission directivity discussion, it is interesting to note that the phase velocity (C_{ph}) decreased with decreasing frequency much in

the same way that Mollo-Christensen and Narasimha[33] suggested convection and refraction carried the lower frequency sound waves into regions of slower mean flow before being emitted to the surroundings. We propose that there is an interaction between the coherent structure's axial wave speed and the peak sound emission angle (Φ) such that lower wave speeds result in lower angles.

Acoustic Phase Measurements

To determine if the noise measured was indeed produced by the coherent structure in the jet, acoustic phase measurements were made. These were performed by artificially exciting the jet and cross correlating the microphone signal at various locations in the acoustic field with the exciter input signal. From this measurement a phase relationship was obtained. This procedure yielded limited success in this study, however, we are currently improving our data reduction techniques in order to obtain more extensive results. The results that we were able to obtain are shown in Figure 11. This figure shows segments of acoustic phase fronts obtained when the jet was excited at a frequency of St=0.316. The fact that acoustic phase fronts could be measured indicates that some of the noise produced by the jet is directly related to the coherent structure. Using a ray tracing technique described by Schubert[34], the apparent origin of the coherent noise is

in the potential core region of the jet. This happens to be the region where the flow fluctuations reached their maximum level.

IV. CONCLUSIONS

Acoustic measurements revealed that the major noise source in the M=0.6 jet appears to be located near the end of the potential core. This corresponds to the axial location where the flow fluctuations reach a maximum level. This result was also obtained by other investigators[1,25]. Overall noise radiated by the jets was found to reach a maximum value around 30° from the jet axis. However, individual frequencies emitted maximum SPL at different angles from the jet axis. As the angle from the jet axis increased, the spectra of the noise shifted to higher frequencies. Axial wave number-frequency measurements were utilized to produce a relationship between phase velocity (C_{ph}) and frequency. It was found that the coherent structure's axial wave speed decreased with decreasing frequency much in the same way the angle of peak noise emission decreased with decreasing frequency. We propose that it was this slowing down of the wave speed that caused the decrease in the peak noise emission angle. The noise production mechanism in the jet was found to be more reponsive to mid-band excitation frequencies. Excitation at these frequencies caused a small increase in SPL at the frequency of excitation, but a much larger increase in full spectrum noise. Segments of acoustic phase fronts were measured indicating that some of the noise produced by the

jet could be directly attributed to the large scale coherent structure. The origin of the phase fronts was found to be located in the potential core region of the jet.

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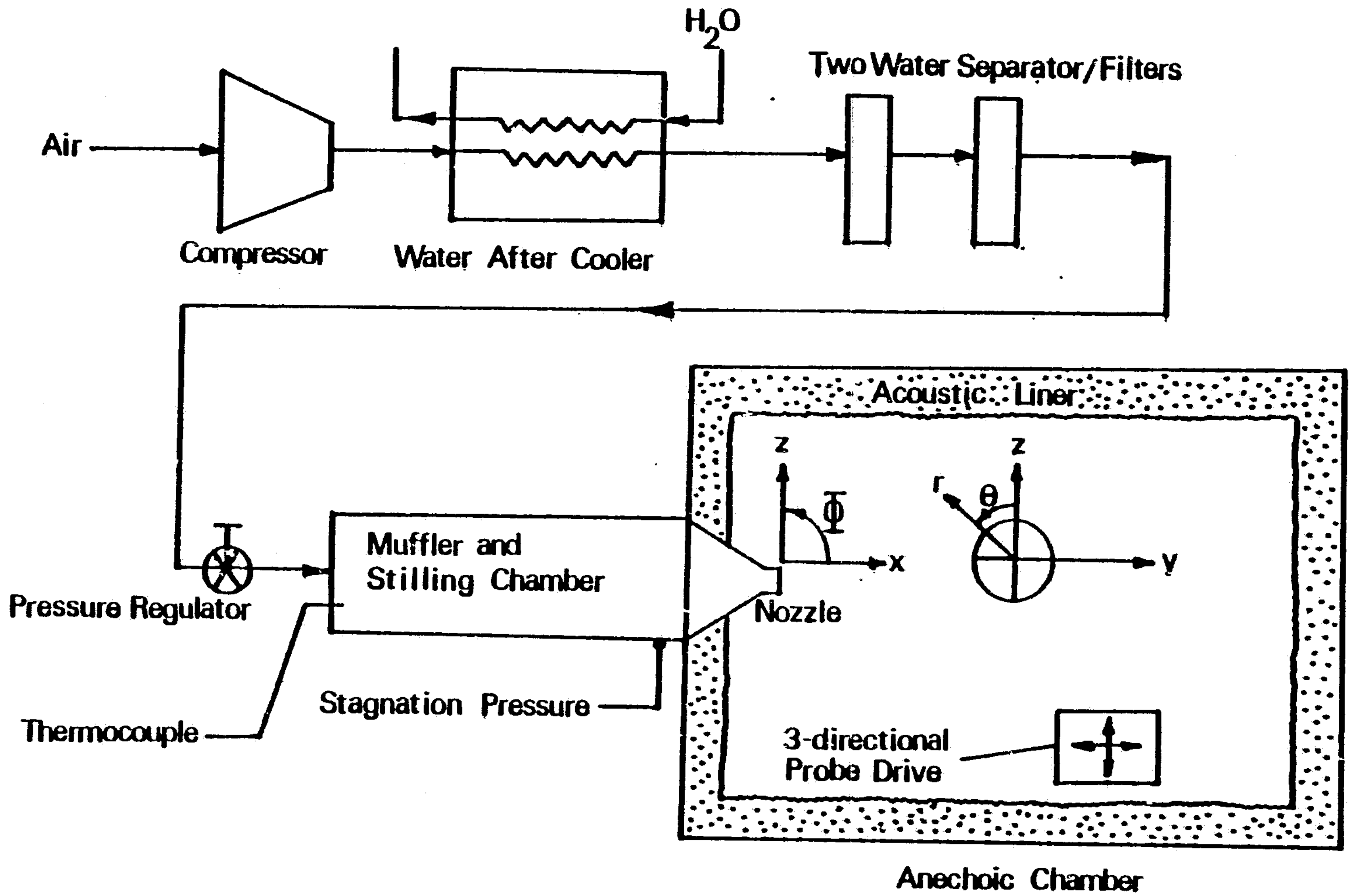


Figure 1. Schematic diagram of jet test facility

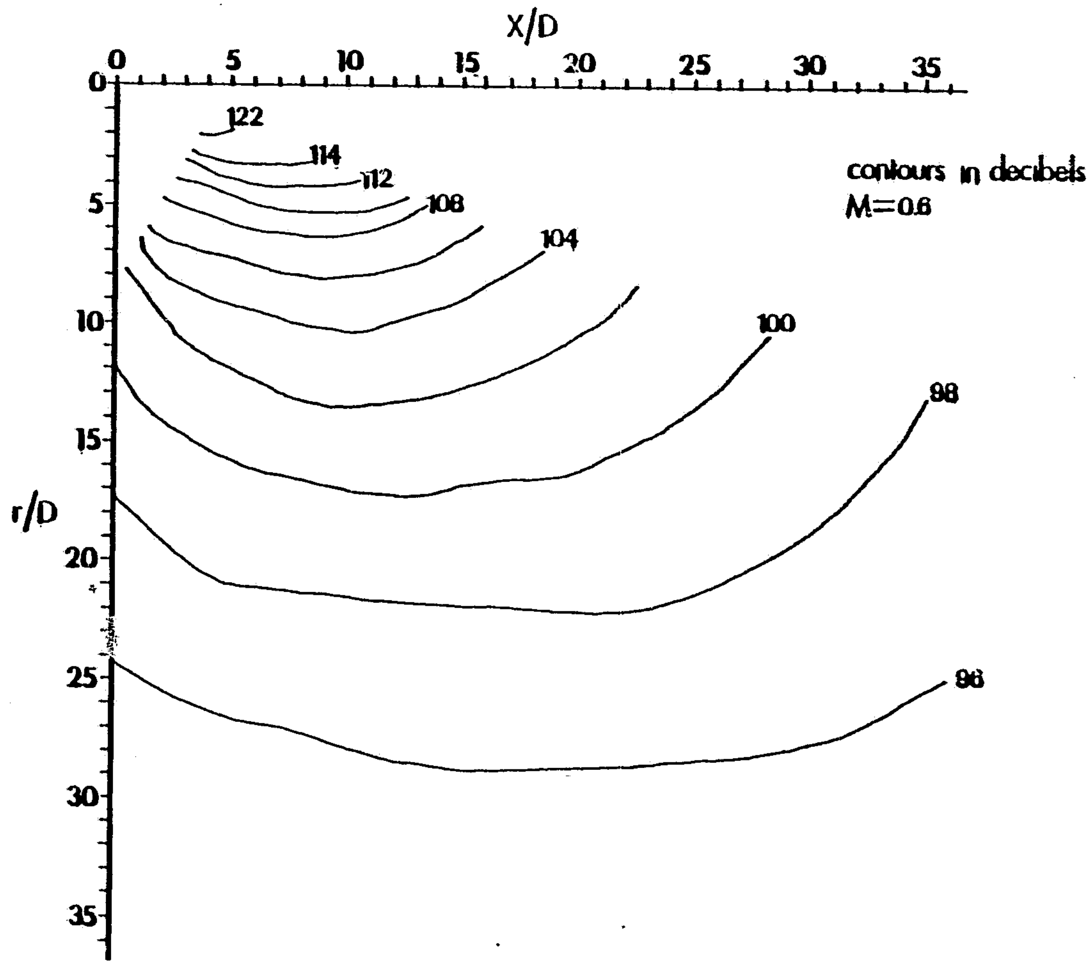


Figure 2. Sound pressure level contours, M=0.6

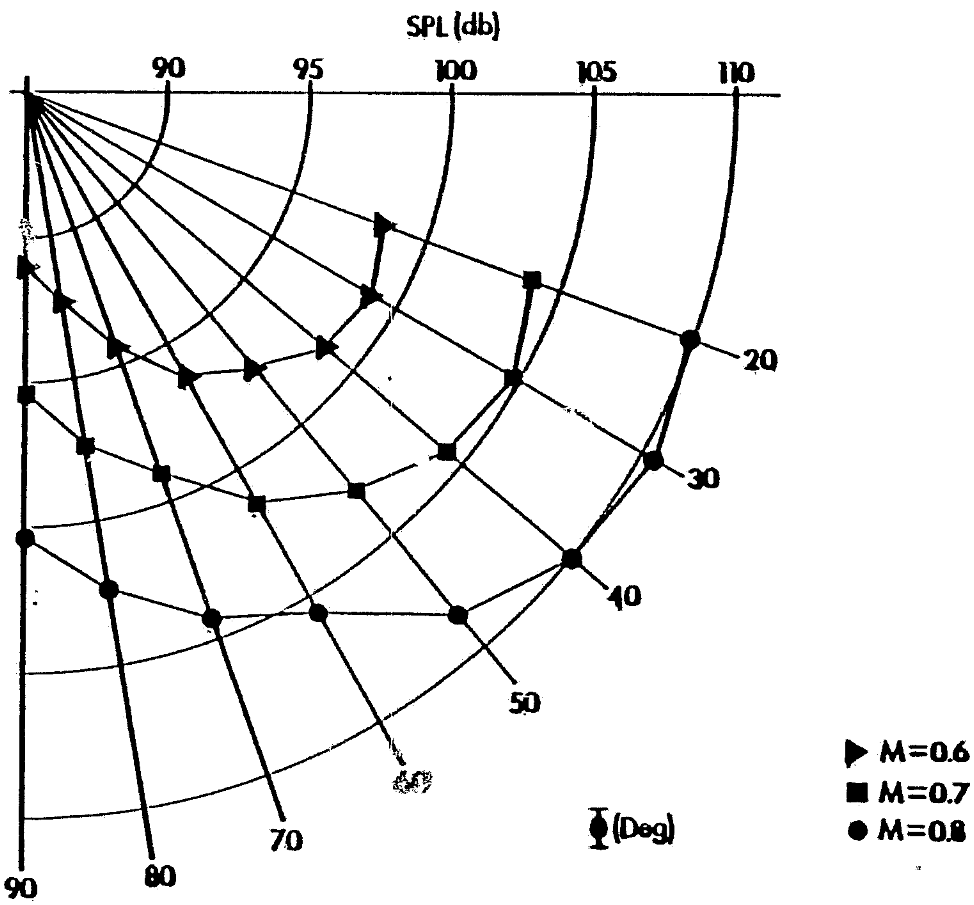


Figure 3. Directivity of full-band sound pressure levels

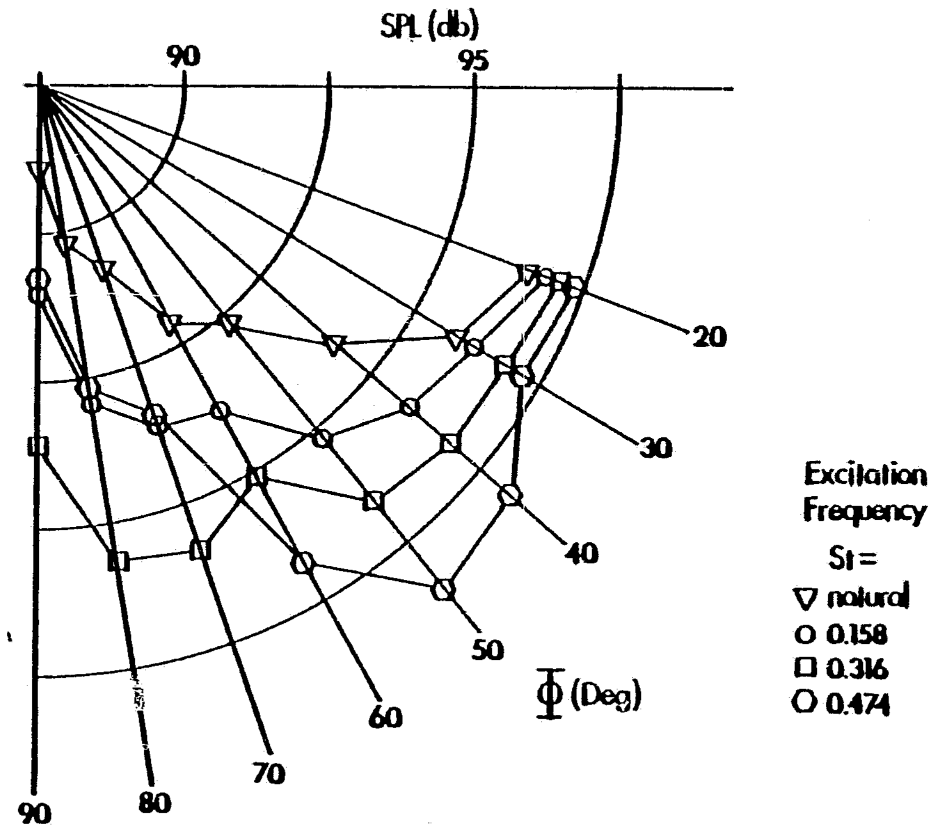


Figure 4. Directivity of full-band sound pressure levels for artificially excited jet, M=0.6

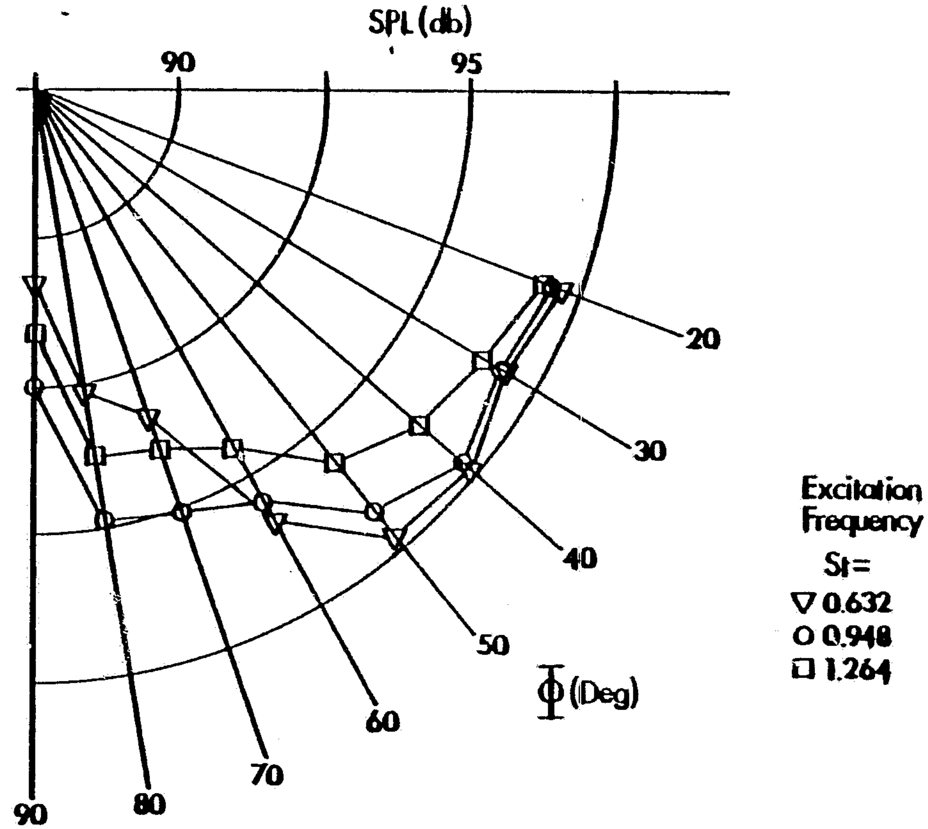


Figure 4. continued

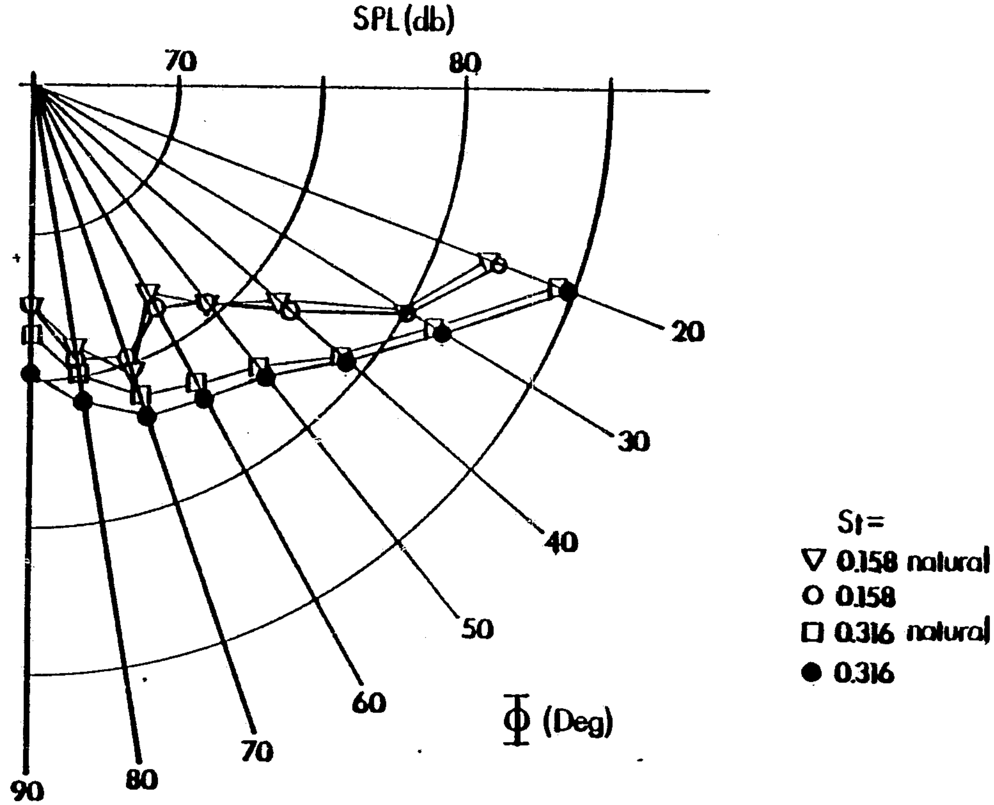


Figure 5. Directivity of individual frequency sound pressure levels for the natural and excited jet, M=0.6

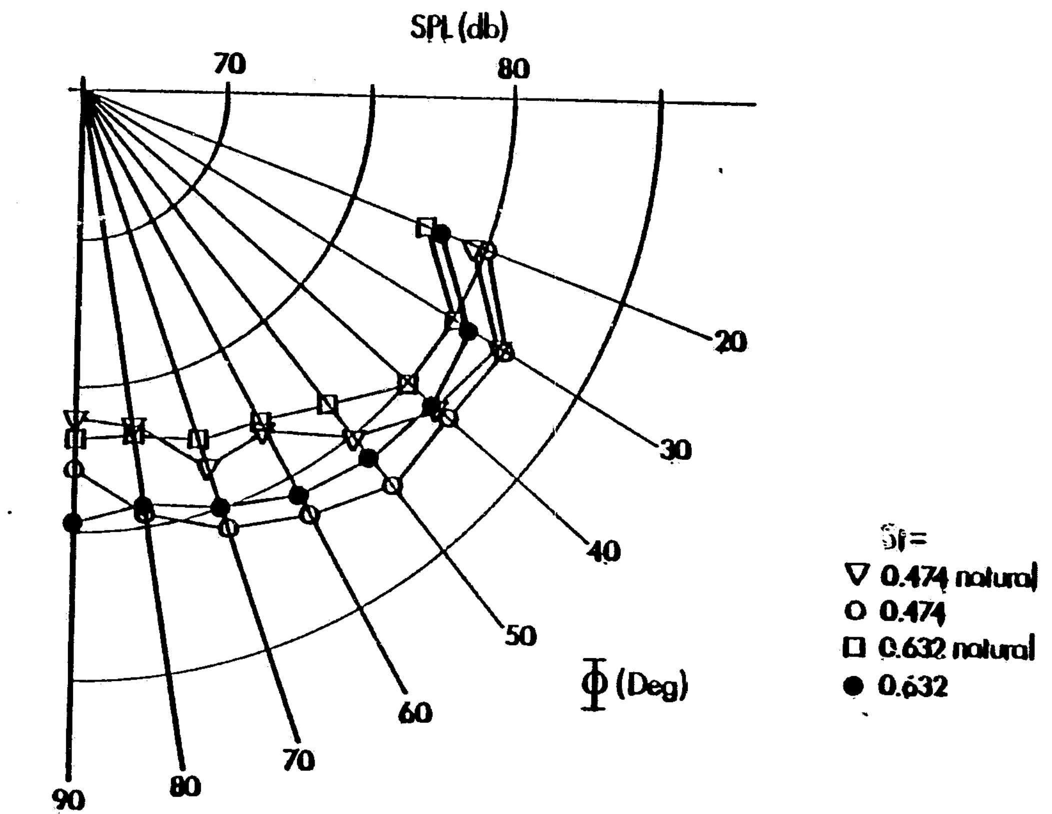
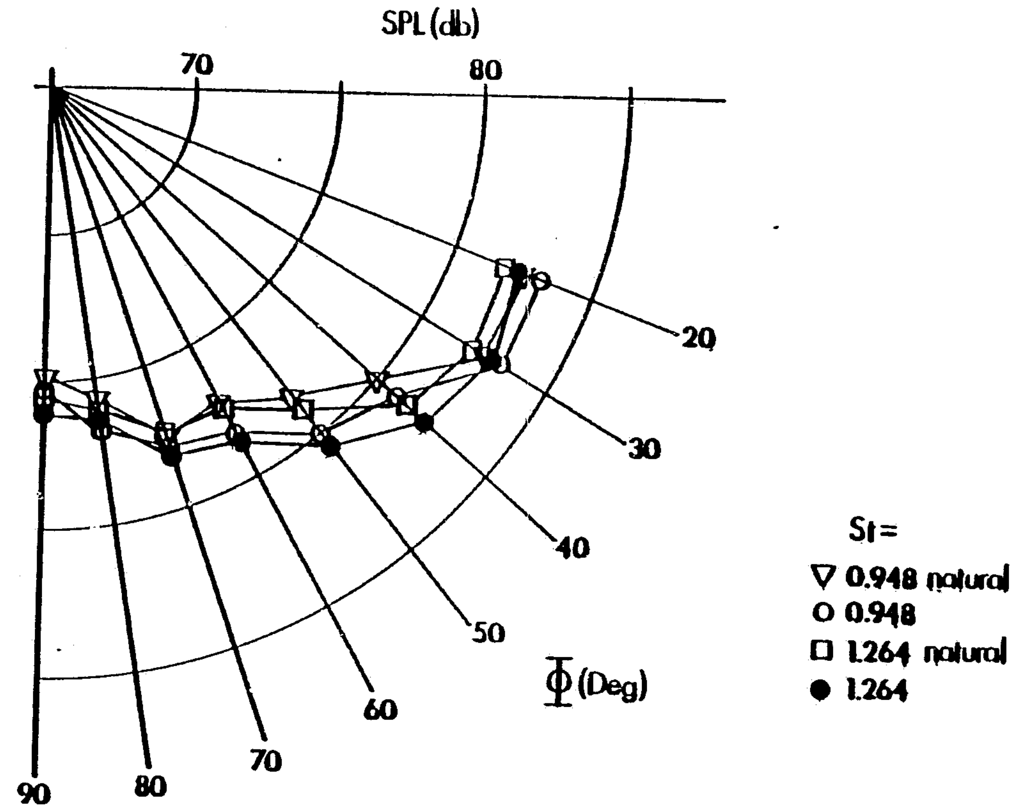


Figure 5. continued



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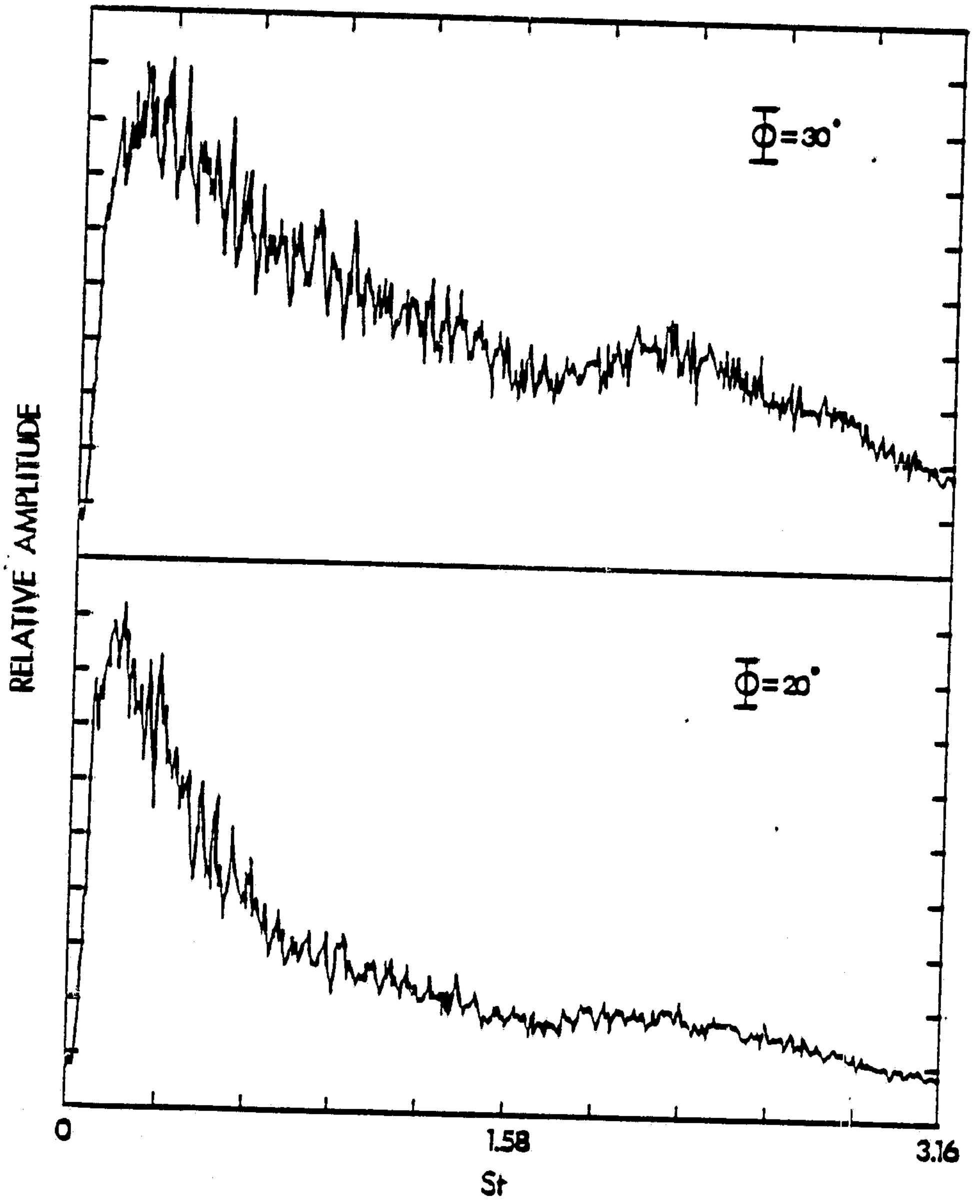

Figure 6. Microphone spectra, M=0.6

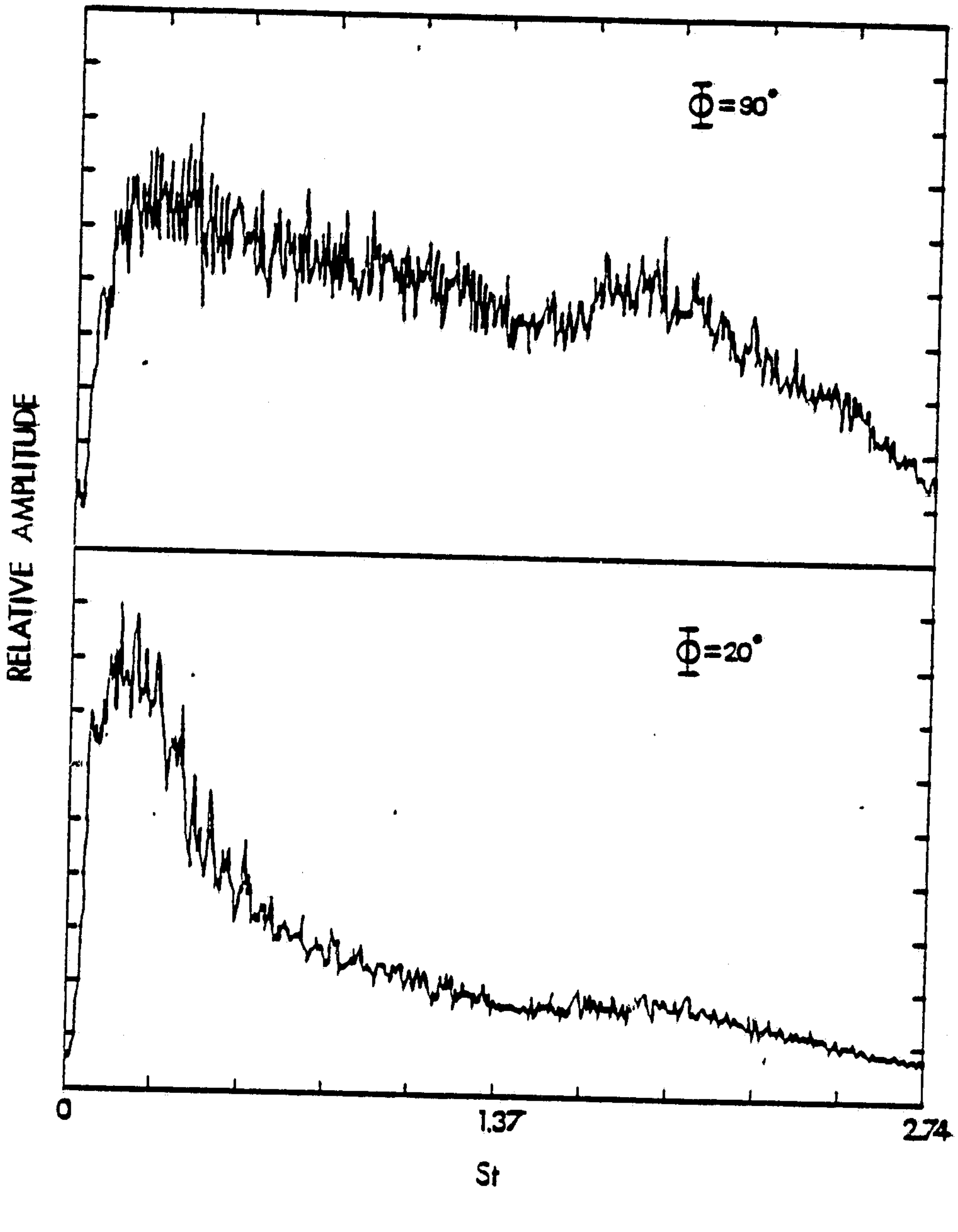

Figure 7. Microphone spectra, M=0.7

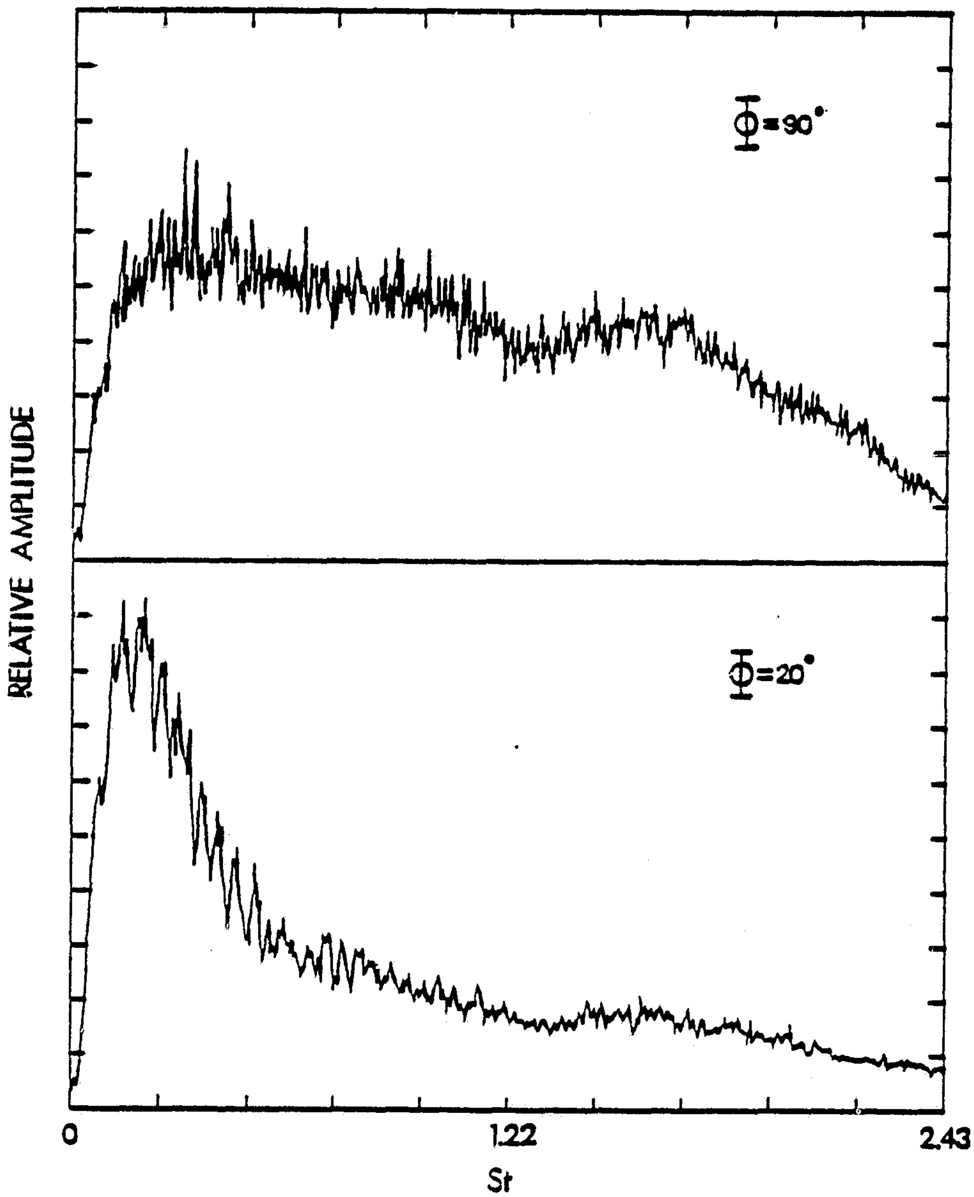

Figure 8. Microphone spectra, M=0.8

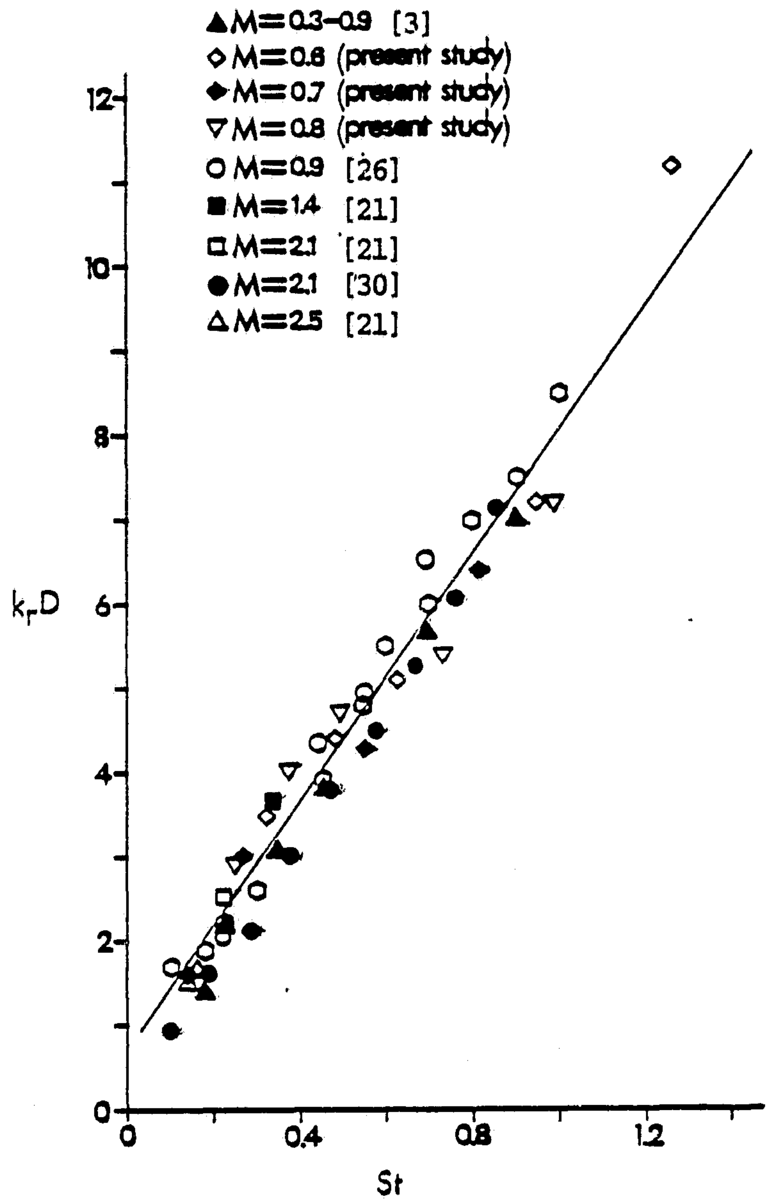

Figure 9. Axial wave number variation with Strouhal number, M > 0.3

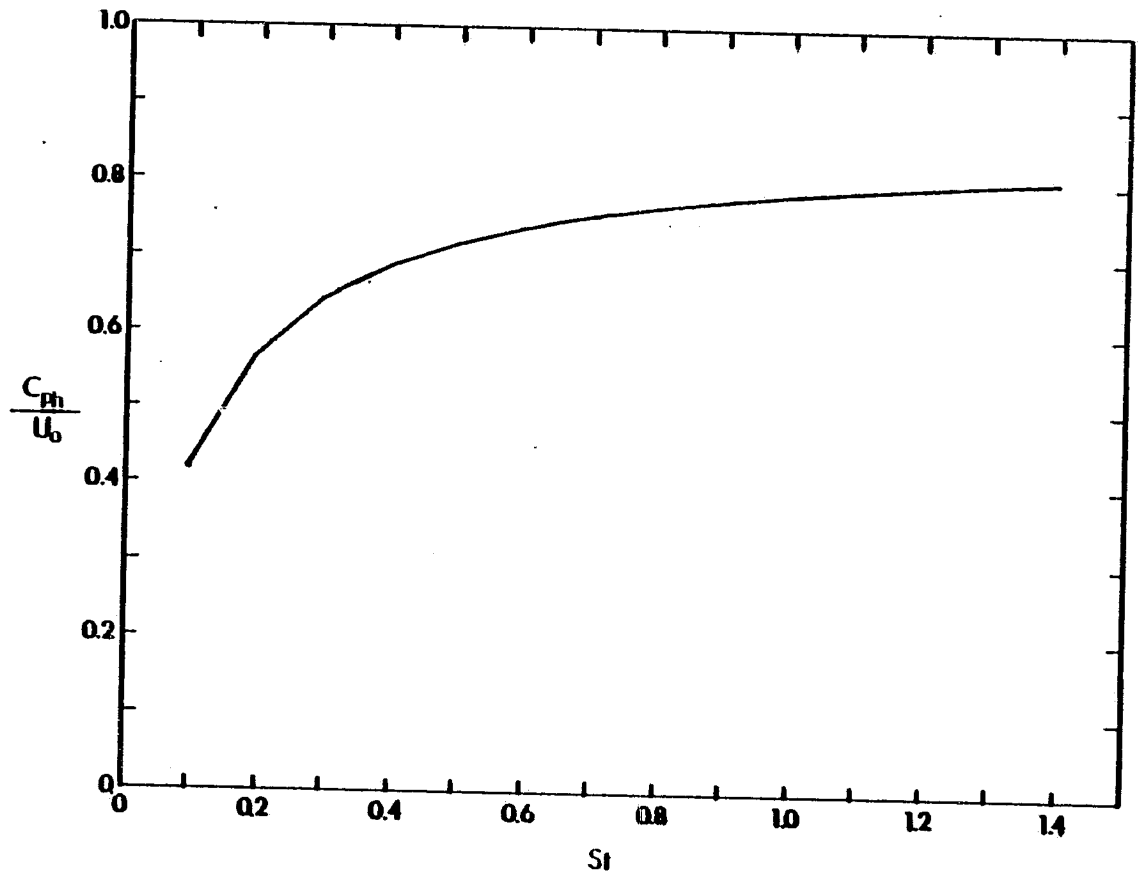

Figure 10. Phase velocity as a function of Strouhal number

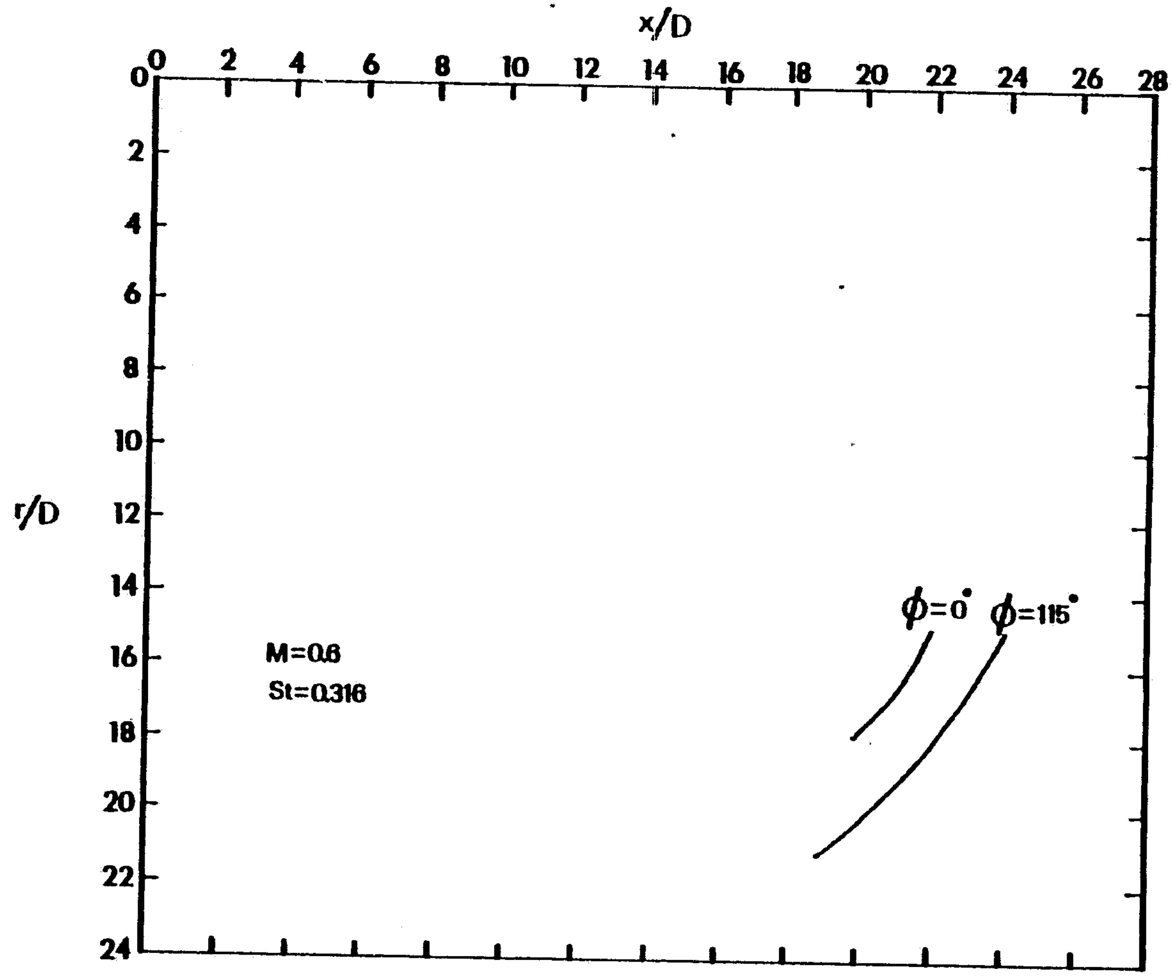

Figure 11. Acoustic Phase Fronts